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Simulation on the effect of the blade number on the rotational characteristic on a horizontal axis river current turbine

Aditya Rachman*, Ridway Balaka, Jenny Delly and Yuspian Gunawan

Abstract

The power system based on the horizontal axis turbines has been extensively employed to harness the kinetic energy of the moving fluid to generate the clean renewable energy in several domains, such as wind, river, and sea. The characteristic of the rotational speed is one of the prominent aspects in designing the power based on the horizontal axis turbine. This is the characteristic that can determine the quantity of the electricity production in the generator on the power technology system. The number of blades is another important aspect in designing the technology. It is believed that the number of blades not only determines the aerodynamic performance, the construction, and the production cost but also the turbine rotational speed characteristics. This study investigates the effect of the blade number on the rotational speed characteristic of a horizontal axis river current turbine. The methodology of generating the investigation is a parametric study using the blade element momentum theory. The result shows that the turbines with low blade number have high rotational speed characteristics while the turbines with high blade number have low rotational speed characteristics. The very low attack angle which yields into a low lift coefficient is one of the factors responsible for the inability of the turbines with high blade number to operate at high rotation. A further discussion on the results on this investigation relating to the hydrodynamic behavior is explored in this study. It is recommended that when a turbine is decided to have a high blade number, the transmission ratio should be high to obtain a high rotation in the generator.

Keywords: River turbine; Design; Blade number; Rotational operation

Background

The role of energy in the economic development in all nations is so indispensible [1,2]. The industry, transportation, trade, and communication will be posing massive challenges without the support of energy. Unfortunately, many regions, especially in developing nations, still seem to pose the problem of energy access. The topography and geography characteristic and the condition of a dispersed population on a region are some main obstacles for an effort on the distribution of energy [3,4].

The power generation based on the river current turbine is one of the clean decentralized renewable technology potential to supply the energy to the regions where the conditions of the topography, geography, and population become the obstacles for the distribution of energy. The working principle of this technology is based on the conversion of the kinetic energy of the river flow into electricity. This technology requires no level difference (head) and less civil works and causes less detrimental environmental impacts than the conventional hydroelectric power [5].

There are two main classes of the turbine configurations: horizontal axis and vertical axis turbines. Some papers [6-10] show the success of several projects in generating the electricity from water flow, such as rivers, tides, and ocean currents using the horizontal and vertical axis turbines. The horizontal turbines have several beneficial features than the vertical turbines. Some of these features are higher efficiency, easier start-up, less torque fluctuations, and higher rotation speeds [11]. A study [11] reports a survey on research, development, and demonstration on the water current turbine technology which is conducted presently or had been dismissed from the stage of the proof concept to the

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commercialization. The results on this survey show that the horizontal axis turbines are more frequently employed than the vertical turbines.

In the mechanism of energy conversion in a modern horizontal turbine, the fluid kinetic energy is intercepted by the rotor blades to produce lift, as shown in Figure 1. This force is utilized to generate a torque, which is used to drive the generator shaft to produce electricity [12,13].

The mechanism of the energy production in the generator is based on the production of the electromotive force (EMF). Faraday's law states that the EMF will increase when a permanent magnet is moved relatively to a conductor, or vice versa, to give the effect of the flux change. The amount of EMF is proportional to the rate of the flux change.

The rotational speed characteristic of the generator shaft plays an essential role in determining the rate of the flux change. This is because the shaft drives one of the two components inside the generator, the conductor or the magnet, to generate the relative movement in order to produce the flux change. The role of the rotational speed characteristic of the turbine is also salient in determining the rate of the flux change. This is because generally the shaft of the generator is connected to the shaft of the turbine via a transmission system. When the turbine rotational speed is high, the rotational speed on the generator shaft is possibly high, making the rate on the flux change to be high and vice versa. Thus, in the design stage of the power technology based on the horizontal axis river current, the turbine rotational speed characteristics should conform to that of the generator rotation speed; otherwise, the rate on the flux change will fail to meet its requirement, and thus, the energy production in the generator is highly possibly unsatisfactory, resulting in an inefficient power technology.

Instead of the aerodynamic performance, the manufacturing cost, and the construction, the design parameter of the blade number seems to have a connection to the rotational speed characteristics of the turbine. Studies [14-18] indicate the role of the rotational speed on the effect of the blade number on the performance of horizontal axis wind turbines. These studies show that the turbines with high blade number perform better at low rotation speeds, while those with lower number obtain high performance at high rotation speeds.

In the water current domain, several papers [6-10,19-21] show some projects on the power technology based on horizontal axis turbines, in some fields such as tidal streams, ocean currents, and river flows, conducted by several companies and universities. Most of these papers provide the detailed information of the number of blades utilized in the projects. However, it seems that the explanation on the connection between the blade number and the turbine rotational speed cannot be found in these papers. Some of the papers seem to focus on the effect of the blade number on the hydrodynamic performance.

A study [8] shows a series of pilot projects on horizontal axis river current turbines by the Northern Territory University, Australia. The projects show that the change in the blade number is always accompanied by the change on the transmission ratio. Turbines with higher blade number require a higher transmission ratio than that of the turbines with lower blade number. This may indicate that the change on the transmission ratio is conducted to maintain the generator rotational speed when the number of blades is varied. A reference [13] explains the relation between the tip speed ratio (TSR), a ratio of the turbine rotational speed and the ambient flow velocity, and the solidity of rotor, a ratio of the area of the blades and the rotor swept area. A rotor with a

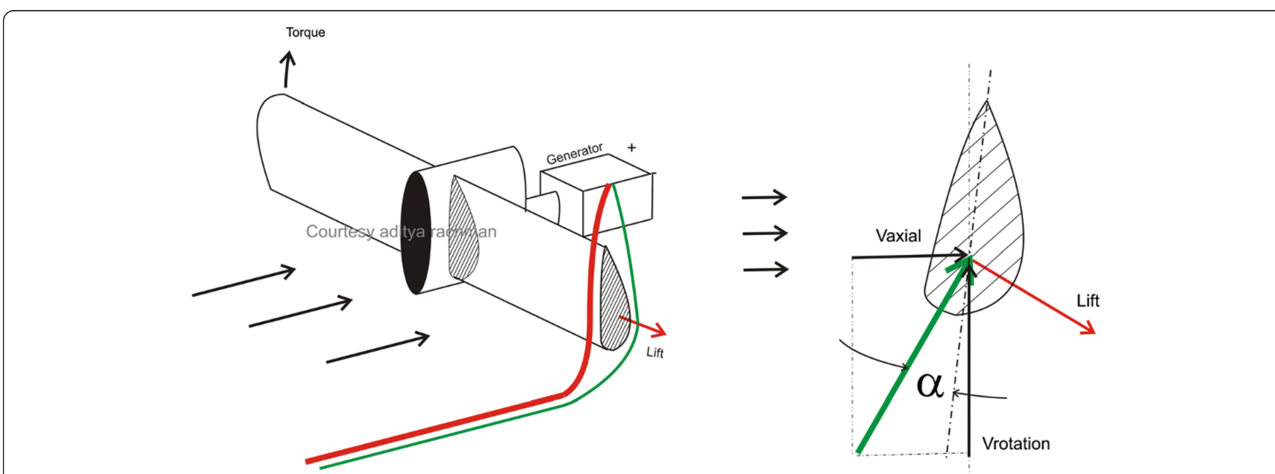

Figure 1 The mechanism of the energy conversion in a modern horizontal turbine. The lift force and the velocity in a blade. Illustrated by Rachman adopted in [12,13].

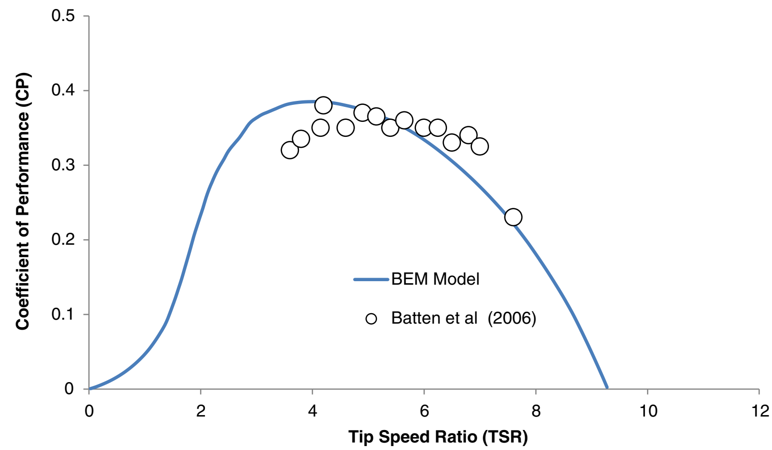

Figure 2 **The results in the validation of the BEM model to the experimental results in [21].**

high speed will have less blade area than the rotor of a slower machine. Another reference [12] explains that a low solidity rotor is intended to obtain a high rotational speed in order to reduce the gearbox ratio. These explanations can assert the indication in the previous references regarding the connection of the rotational speed and the blade number. As the lower bladed turbine will obviously have a less blade area than that of the turbine with high blade number, the rotational speed of the lower bladed turbine will be higher than that of the turbine with high bladed number. Although some of these references can indicate more relationship between the turbine rotational speed and the number of blades, a comprehensive discussion of the phenomenon seems to be less explored.

The knowledge on the behavior on the connection between the blade number and the turbine rotational speed can assist the designer in obtaining an appropriate decision in the design stage, especially in selecting the specification of the generator and the transmission ratio when the blade number is decided, in order to contribute in obtaining a technology with a desirable performance outcome. This study aims to investigate the effect of the blade number on the turbine rotational speed characteristic of the horizontal axis river current turbine. This study also attempts to explore more comprehensively the reasons behind the results of the investigation.

Methods

This investigation is conducted by a parametric study using the mathematical model of the Blade Element Momentum (BEM).

Blade element momentum model

In wind domain, there are many approaches, theories, and models to evaluate the performance of the horizontal axis turbine. The model of BEM is one of the oldest methods and remains to be the most widely used

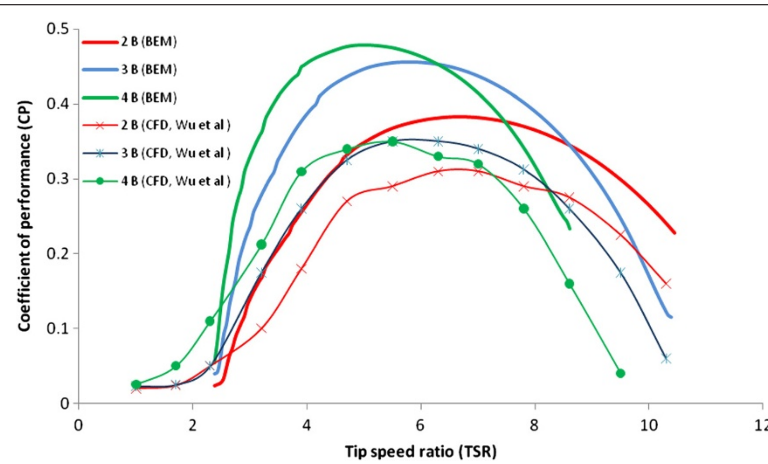

Figure 3 **Coefficient of performance versus tip speed ratio in the variation of blade number.**

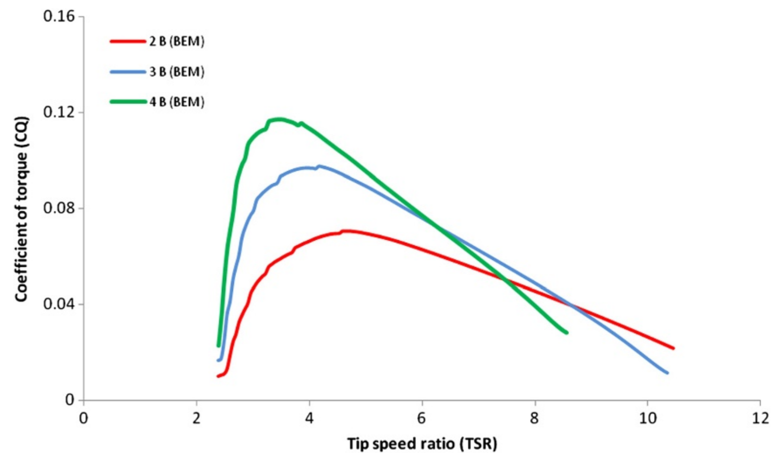

Figure 4 Coefficient of torque versus tip speed ratio in the variation of blade number.

method [22]. This model allows the user to evaluate the force (lift) acting on the blades, the torque in the shaft, and the power at the blade with different wind speeds [23].

It is possible to apply this model into the water domain. One of the reasons is the similarity in the working principle of the horizontal wind turbine and that of the water current turbine [24]. The mechanism of the water current turbine is to extract the kinetic energy of the flow of water, similar to the mechanism in the wind turbine. According to [25], the mathematical equation of the water current turbines is analogous to the wind turbines.

The development of BEM model is based on the combination of the momentum theory and the blade element theory [12,13]. The momentum theory is developed form the Bernoulli equation and the momentum balance equation. Both equations can be applied into not only air but also water. The blade element theory is based on the equation of lift and drag forces on the cross section of a blade. In water domain, the lift and drag force mechanism has been applied in several applications such as the boat propeller and the wing on the boat hull.

Validation of BEM model

To validate the BEM model, before being utilized in the investigation, a result from a parametric study using the BEM model will be compared to the experimental result obtained from a study in [21]. In this parametric study, the blade number is set to be three with the diameter of 0.8 m. The blade angle is 25° at the hub and 5° at the tip (twisted). The hydrofoil type is NACA 638xx. The water velocity is 1.54 m/s. These data are similar to those in [21].

It is shown that the data obtained from the BEM model and those of the experimental result in [21] show a good agreement (see Figure 2). It can be seen that the curve resulted from the BEM model is close to some of the data in the experimental result.

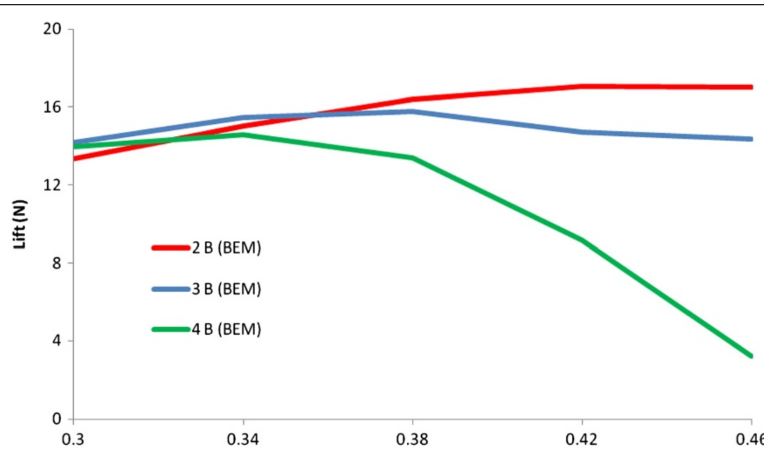

Figure 5 Lift forces versus radius (> 0.3 m) in different blade numbers in TSR 11.

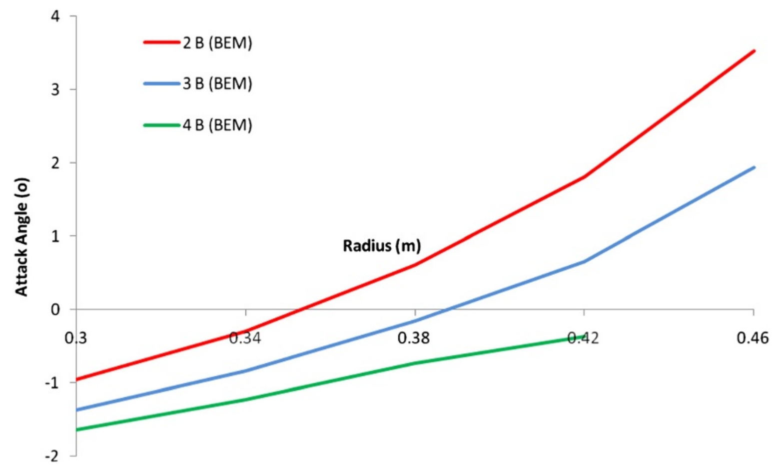

Figure 6 Attack angles versus radius (> 0.3 m) in different blade numbers in TSR 11.

Data of investigation

In the investigation on the effect of the blade number to the rotational speed characteristic of the river turbine employing BEM model, the input parameter of the turbine radius is 0.3 m and the hub radius is 0.07 m. The hydrofoil type is NACA 63415. The data of the drag and lift coefficients of this hydrofoil are obtained from [26]. The blade width is 0.14 m at the hub and 0.02 m at the tip (tapered). The blade angle is 23° at the hub and 0° at the tip (twisted). The water velocity is 2 m/s. The rotational speed of the turbine is varied from 0 to 400 RPM. The number of blades is varied by two, three, and four.

The result of this parametric study is presented in a graph illustrating the variation of the rotational speed of the turbine blade, represented by TSR and the blade number on the coefficient of performance generated. To validate the result of this study, it compares to the computational results obtained in [20]. To obtain additional information that can be used to explain the reasons of the investigation results, this study presents the data of the lift force, the axial rotor flow velocity, and the attack angle. These additional data are obtained during the calculation of the coefficient of performance using the BEM model.

MATLAB program is employed to calculate the coefficient of performance and the additional data as required by the iteration process in some of stages of the BEM calculation.

Results and discussion

The results on the investigation using BEM model show a good agreement to the computational results in [20]. Even the amount of the coefficient of performance is different; both numerical results show a similar tendency of the higher rotational speed range of the turbine with lower blade number than that of the turbine with higher blade number. This is because the power is still possible to be generated at the high rotational speed for the low-bladed turbine.

The turbine with two blades possibly operates at TSR of more than 11, while the turbine with four blades

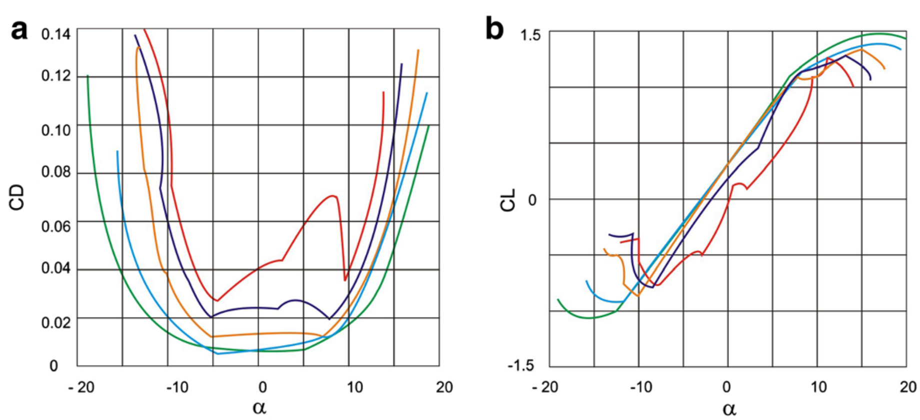

Figure 7 The coefficients of (a) drag (b) lift of NACA 63415.

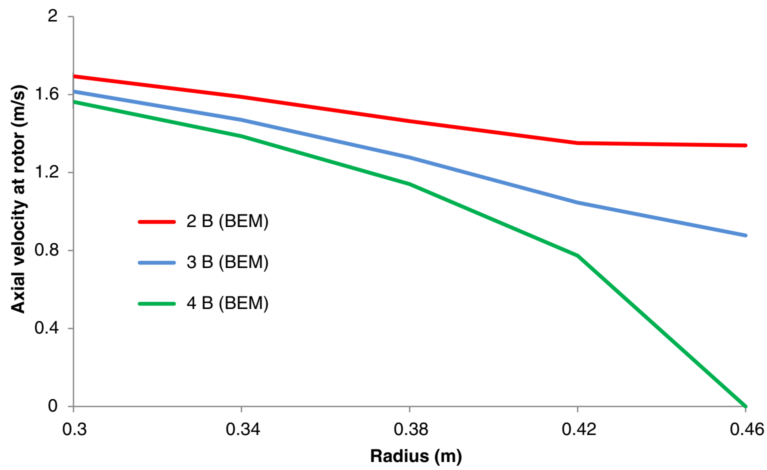

Figure 8 Axial velocities versus radius (> 0.3 m) in different blade numbers in TSR 11.

seems impossible to operate at TSR of more than 11 (Figure 3). The turbine with two blades still possibly produces the power at TSR of more than 11 as the torque can still be generated at a corresponding rotation condition (Figure 4). In contrary, the torque generated for the turbine with four blades at TSR of more than 11 seems to be highly impossible; thus, the turbine seems to be impossible to generate satisfactorily the power beyond TSR of 11.

At a high rotational speed (TSR 11), the lift forces in high radius for the turbine with four blades tend to be very low (see Figure 5). This results in the low torque generated of the turbine at the high rotational speed. For the lower bladed turbines, the lift forces in high radius are still relatively high at the high rotational speed, making the turbines maintain the torque at corresponding rotational speed.

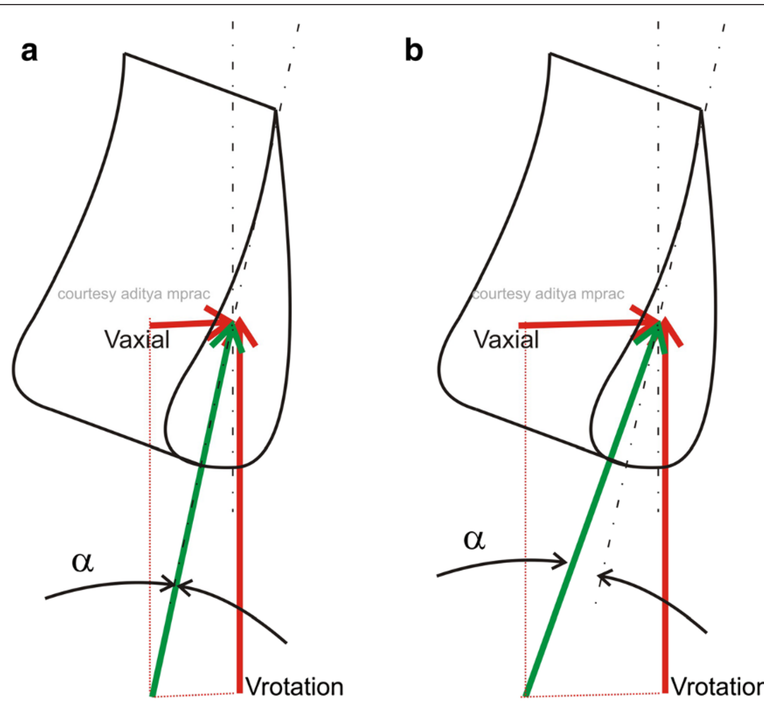

Figure 9 The condition of attack angle and axial velocity at a high rotational speed. (a) High-bladed turbine. **(b)** Low-bladed turbine.

At corresponding rotational speed condition, the attack angles of the turbine with four blades in high radius are very low (negative) (see Figure 6). This results in the low lift coefficient. This is due to the value of the lift coefficient for the NACA 63415 that would be low, even negative, at the very low attack angle (see Figure 7b). As the lift coefficient is low or even negative, the lift generated will be low or possibly be negative. For the turbines with lower blade number, the attack angles for the high radius are relatively not too low. This possibly makes the lift still possible to exist, thus making the turbines to still generate the torque at the high rotational speed.

At TSR of 11, the axial velocities at rotor in the high radius for the turbine with four blades are much lower than those of the turbines with less blade number (see Figure 8). This low axial velocity may cause the low attack angle. The following paragraph explains the relation of the low axial velocity at rotor and the low attack angle for the high-bladed turbine at the high rotational speed.

In the BEM model, the amount and the direction of the wind acting on the turbine blade depend on the sum vector of the axial velocity and the blade rotational speed. As both velocities (the axial velocity and the rotational speed) are perpendicular with each other, in the condition of the very low axial velocity and the high rotational speed, the position of the velocity acting on the turbine blade tends to be closely parallel to the rotational speed. This causes a low attack angle (see Figure 9).

The condition of the low axial velocity at the high rotational speed for the turbine with high blade number could be the blockade effect created by the number of blade area interacted with fluid. For the turbines with lower blade number, the blockade effect is relatively less. This makes the lower bladed turbines possible to obtain a relatively higher attack angle at the high rotational speed than that of the high-bladed turbine.

Conclusion

This study has investigated the effect of the blade number on the rotational speed characteristic of a horizontal axis river current turbine. Following are some conclusions that can be drawn.

The small number of blades allows the turbine to operate at the high rotational speed; in contrast, it is impossible for the turbine with high blade number to operate at the high rotation. One of the factors responsible is the inability of the high-bladed turbine to generate the power at the high rotational speed. This is because the attack angle at corresponding rotational speed is very low, resulting in low lift coefficient. In contrary, for the turbine with less blade number, it is possible to obtain a relatively more moderate attack angle at the high rotational speed, to allow the turbine obtaining the high lift coefficient at the high rotation speed.

The low rotational speed characteristic for the high-bladed turbine requires a high gearing ratio for the mechanical transmission system. As a result, it is possible to obtain high looses as more friction surfaces can exist caused by the requirement of the multi-gearing system. This may, thus, reduce the overall river power performance. In addition, the high ratio may add the dimension of the transmission on the power based on river current; thus, it may increase the weight which in turn influences the construction consideration.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

AR developed a mathematical code for BEM Calculation in MATLAB. AR and RB conducted the parametric study, collected the references and the informations, and drafted the manuscript. JD and YG corrected the draft manuscript. All authors read and approved the final manuscript.

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